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Mechanical and Tribological Properties of Carbon Fiber/ Glass Fiber-Reinforced Epoxy Hybrid Composites Filled with Al_2O_3 Particles

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This article has been checked for similarity.

ABSTRACT

In this study, we produced Aluminum oxide (Al_2O_3) reinforced carbon fiber and glass fiber reinforced polymer (CFRP, GFRP) composites and investigated mechanical and tribological properties. Al_2O_3 was dispersed in epoxy resin using a mechanical stirrer. The composites are produced via the hand lay-up method and dried at room temperature for 48 hours. The properties of composites were determined via Archimedes' method, flexural, impact, hardness and wear tests. The highest flexural strength and hardness were found at 946.3 MPa and 48.7 HBA for 3 wt.% Al_2O_3 reinforced CFRP, respectively. The highest impact strength was observed at 187.4 kJ/m^2 for an un-reinforced GFRP composite. The lowest Coefficient of Friction (COF) and wear depth was found 3 wt.% Al_2O_3 reinforced GFRP composites.

Keywords:
Aluminium oxide; CFRP; Epoxy; GFRP; Hardness; Impact strength

INTRODUCTION

Polymers and their composites are used in many common and advanced engineering applications. They are becoming a good alternative to products made out of metal due to several attractive properties, including lightweight, high strength, ease of processing, low waste of material during manufacturing, and cost-effectiveness. As a result, major efforts have been made to use polymers in diverse industrial applications, using a variety of reinforcements, including fibers, to boost the physical and mechanical properties of the polymers. As a result, fiber-reinforced polymer matrix composites are extremely appealing due to their low friction coefficient, biodegradability, high strength, high stiffness, good corrosion resistance, and low weight. These materials are currently used in almost all aspects of daily life, from homes to aerospace applications(1-3).

Fiber-reinforced polymeric composites have become widely accepted for application in various sectors, including infrastructure, automotive, aerospace, and, most recently, oil and gas. Due to their high strengths and low densities, and ease of manufacture, polymers and their composites are being used more frequently. When compared to traditional metallic systems, these materials are appealing due to two key properties. They can be customized to have stacking sequences that offer high strength and stiffness in directions of heavy loading, despite having a relatively low density. Composite materials are made of resin and reinforcement that is chosen for the application and the desired mechanical qualities (4-7).

The reinforcement of fiber-reinforced materials is chosen from carbon, glass, basalt, wood, paper or aramid, while the matrix is selected from various resins (epoxy, polyester, phenolic, vinyl ester, etc.) While the matrix encloses and protects the fibers, the fibers generally act as the primary load-bearing element. Matrices serve as load-transfer components between the fibers, shielding the structure from adverse environmental situations like high temperatures and humidity(8, 9).

Carbon fiber and glass fiber-reinforced polymer (CFRP/GFRP) composites have been frequently used in the aviation and space industry. As a result of their outstanding qualities, including their high strength, flexibility and stiffness, low weight, and excellent fatigue resistance. Glass fibers (GFs) work well under high tensile stress but aren't strong enough for compression

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because of their fragile character. Conversely, plastic materials can handle compression loading very well but cannot resist high tension. The GFRP created by combining these two materials creates a composite material that can withstand compressive and tensile loads. The use of GFRP composites in thermal, electrical and sound insulation, sporting equipment, boat and ship construction, aerospace applications, automotive, and sheet molding compounds is growing as a result of these features. Carbon fibers (CFs) are carbon-based fibers with typical properties such as high tensile strength and stiffness, low weight, high-temperature tolerance, low thermal expansion and great chemical resistance. CFRP composite materials are being used in a growing variety of aircraft components. In comparison to other types of fibers, CFs have a higher success rate and are light in nature(8-11).

High toughness and strength, adhesion, durability at low and high temperatures, low moisture absorption, thermal stability, high chemical, electrical and corrosion resistance, low shrinkage, good adherence to a variety of substrates, and simplicity of production are only a few of the advantages of epoxy. Epoxy is widely used in various products, including adhesives, construction, petrochemicals, automotive, aeronautics, semiconductor encapsulation, biocompatible implants, protective coatings, laminates and electric and electronic systems. Epoxy has excellent properties but a fragile structure, poor tribological performance, limited flame resistance, and low crack strength. The two main methods used to solve the problem are chemical treatment and the addition of second-phase particles (12-18).

Three main ways are often used to evolve the features of polymer matrix composites: the kind of polymer, the types of particles and fibers, and the interface between fibers. By incorporating fillers (such as Aluminum Oxide (Al_2O_3), Titanium Oxide (TiO_2), WC, SiC, and Graphite) into epoxy, the mechanical characteristics of epoxy are improved without changing the glass transition temperature. Al_2O_3 is widely used in the electronics, chemistry, chemical engineering, and aerospace industries due to its exceptional mechanical properties, chemical stability, excellent thermal properties, cost-effectiveness, good corrosion resistance, and enormous electrical properties. However, this material's fracture durability precludes its use in critical structural applications. (13, 14, 19-21).

Some recent works have studied GFRP/CFRP composites reinforced with Al_2O_3. Asi et al.(22) prepared Al_2O_3 (0, 2.5, 7.5, 10, 12.5 and 15 wt.%) reinforced GFRP composites and investigated the mechanical properties. They observed that the tensile strength decreased with the increasing wt.%Al_2O_3. Al_2O_3-reinforced GFRPs' tensile strengths are lower than the unreinforced GFRP composite. However, the highest bending strength was found in a 10 wt.% Al_2O_3 reinforced GFRP composite, and an increase of approximately 33% occurred compared to the unreinforced specimen. Mohanty et al.(23) fabricated nano-Al_2O_3 (0, 1, 2, 3, 4 and 5 wt.%) reinforced Glass/Carbon fiber epoxy composites and investigated composites' mechanical behaviour. They determined that composites' tensile strength decreases with the reinforcement of Al_2O_3. Raju et al.(24) produced GFRP reinforced with Al_2O_3 (0, 5, 7.5 and 10 wt.%) composites and analyzed mechanical and tribological behaviour. They observed that Al_2O_3 reinforced enhanced composites' tensile strength (254 to 352 MPa), hardness (63 to 72 Shore-D) and wear resistance. Nayak et al.(25) prepared Al_2O_3/SiO_2/TiO_2 (10 wt.%) reinforced GFRP composites and investigated mechanical properties. The highest hardness and impact energy were found for Al_2O_3-reinforced GFRP composites. Patel et al.(26) prepared Al_2O_3 and SiC (5 wt.%) nanoparticles reinforced GFRP and studied tribological features of the composites. As a result of the wear tests, the lowest wear loss was found in Al_2O_3-reinforced GFRP composites at all applied normal loads and sliding speeds. Zhang et al.(27) focused on the tribological properties of the nano-Al_2O_3 (2, 4, 6, 8 and 10 wt.%) reinforced CFRP composites it produces. Based on their research, they found that reinforcing 4 wt.% Al_2O_3 decreased the rate of wear and the Coefficient of Friction (COF) by 74.7 % and 65.5 %, respectively when compared to the unreinforced CFRP. Kaybal et al.(28) researched mechanical strength of the nano-Al_2O_3 (1, 2, 3, 4 and 5 wt.%) reinforced CFRP. According to this study, the tensile strength and flexural strength reach the highest values with 2 wt.% Al_2O_3 reinforcement.

In the present investigation, we were produced hybrid (Al_2O_3-GFs/CFs) reinforced epoxy matrix composites via the hand lay-up method. This study aims to obtain the optimum reinforcement amount to achieve the produced composites' highest mechanical and tribological properties.

MATERIALS AND METHOD

The epoxy resin (Epikote Resin 828 Lvel) is used with the hardener (Epikure Curing Agent 866) to produce composites. The mixing ratio for epoxy resin and curing agent is 3:1, respectively. Twill CFs (200 gr/m^2, fiber diameter: 7μm, laminate thickness: 0.327 mm) and twill GFs (200 gr/m^2, laminate thickness: 0.15 mm) were used. Al_2O_3 powders (Eti Aluminum, +98.5%, particle size:-100 mesh, Bulk Angle:32-36^o, Cas:1344-28-1) are used as reinforcement.

In this study, we used the same production route to fabricate varying composites. Firstly, Al_2O_3 was dispersed in epoxy resin for 4 min using a mechanical stirrer. CFs and GFs were cut to the size of 250 mm length and 250 mm

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width. The epoxy curing agent is added to the Al_2O_3-epoxy mixture. The mixture was applied to CFs and GFs with a brush and after that, the composite was cured at room temperature for 48 hours. In this procedure, 4-layer hybrid composites were produced; the GFs-reinforced samples' thickness is approximately 2.2 mm and the thickness of the CFs-reinforced samples is about 1.1 mm. The composition of composites with reinforcement and sample codes are given in Table 1. While generating the sample code (XY), X represents the type of fiber (C: CFs and G: GFs) in the composite and Y represents the amount of Al_2O_3 (wt.%) in the composite.

Table 1. Sample codes and composition of composites

Sample Code	Epoxy:Fiber (wt.% ratio)	Fiber Type	Al_2O_3 (wt.%)
C0			-
C3		CFs	3
C5			5
C7			7
G0	1:1		-
G3		GFs	3
G5			5
G7			7

The epoxy matrix composites' densities were determined according to Archimedes' method in an ethanol medium and mean values were calculated based on three measurements. The fabricated samples were machined to Charpy impact test (l:80 mm x w:10 mm x t:4 mm), flexural strength (l:80 mm x w:10 mm x t:4 mm) and Barcol hardness test by the respective ISO 179-2, ISO 178-3 and ISO 59, respectively. We used a Devotrans Charpy Impact Tester for the impact test, AVK MH1/AS-102 for the 3-point bend test (The maximum load cell capacity: 500 kp) and Barcol Impressor for the Barcol hardness test. Images were taken from the fracture surfaces of the specimens after the impact testing with the Leica M-125 stereomicroscope. Reciprocating dry sliding wear tests were performed in a Bruker™ UMT2 Tribometer under 3 N force with 5 mm/s speed for 20 m of total distance by using 5 mm diameter chrome steel balls (ASTM E52100). Wear depths were obtained by examining the change in Z-axis values on the device. The processing and characterization of epoxy matrix composites are given schematically in Fig.1.

RESULTS AND DISCUSSION

Table 2 illustrates the density values of the composites. Relative density values for the produced specimens are between 94.05% and 80.27%. The relative densities of GFRP composites are always lower than CFRP composites. The highest relative density was observed in the C0 specimen. The relative density of CFRP composite specimens decreased with the reinforcement of Al_2O_3. Nayak et al.(29) prepared nano-Al_2O_3 (0.1, 0.3 and 0.7 wt.%) reinforced GFRP composites, and observed that an increasing Al_2O_3 amount increased the void content. Because of their higher viscosity, highly reinforced materials are more difficult to mix and are more likely to produce voids(30). Also, this could be because the entrapped gas could not get out of the epoxy matrix throughout the production and curing processes(29).

Table 2. Relative density of CFRP and GFRP composites.

Sample Code	Theroretical Density (g/cm^3)	Relative Density (%)
C0	1.46	94.05
C3	1.5	90.95
C5	1.528	87.16
C7	1.551	85.01
G0	1.909	84.83
G3	1.946	80.27
G5	1.984	83.43
G7	1.850	84.06

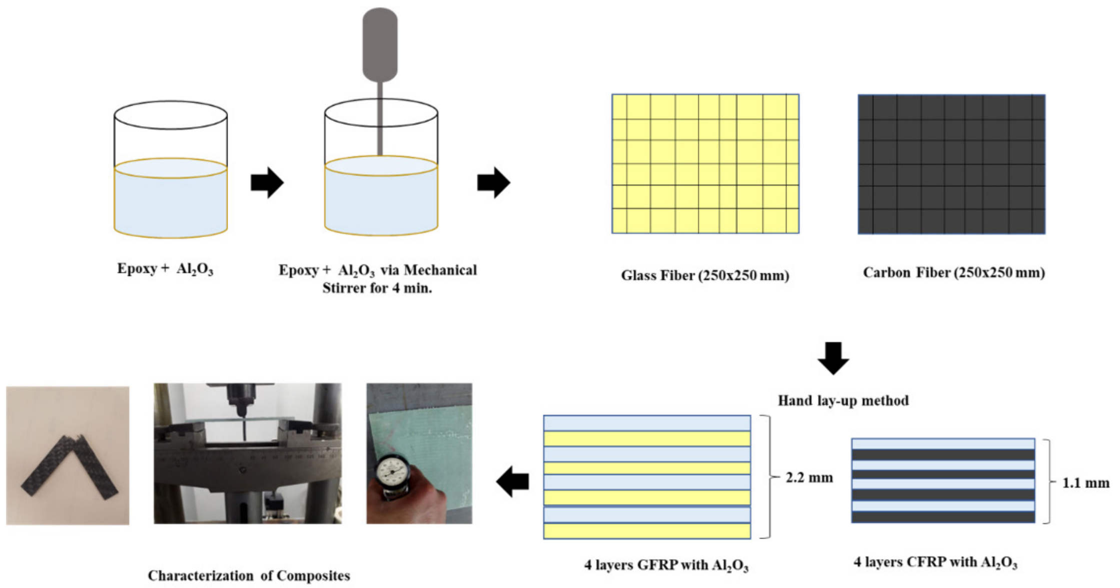

Figure 1. Processing and characterization of epoxy matrix composites

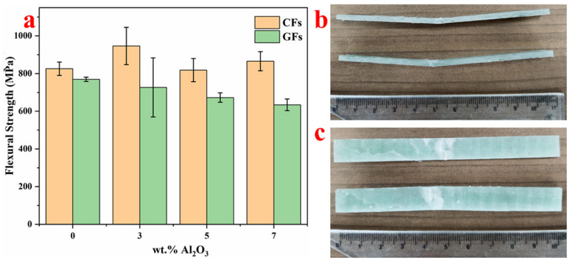

Figure 2. Flexural strength performance of epoxy matrix composites (a) flexural strength of the composites (b,c) image of specimens after testing

The 3-point bending test results of the composites are given in Fig. 2. The data shown are the average of three tests for each sample type. Flexural strength is determined between 946.3 and 634.1 MPa. The highest flexural strength values are obtained for 3 wt.% Al_2O_3 reinforced CFRP composites. With the addition of 3 wt.% Al_2O_3, the flexural strength increased by 15% compared to the unreinforced CFRP sample. However, Al_2O_3 reinforcement above these amounts affected the flexural strength adversely for CFRP composites. Unlike the CFRP, Al_2O_3 reinforcement decreased the flexural strength of GFRP composites and this decrease increased with increasing Al_2O_3 content. This is because as the Al_2O_3 content increases, the void content and Al_2O_3 particle agglomeration also increase, which can cause matrix swelling and the development of microcracks at the interface(29, 31). Moreover, the lower flexural properties may have been brought on by the filler's and epoxy resin matrix's poor interface bonding(22). Similar results are also available in the literature. Wang et al. prepared Al_2O_3 reinforced CFRP and analyzed flexural strength and they determined that the maximum flexural strength was 760 MPa with 15 g/m^2 (areal densities of Al_2O_3) Al_2O_3 reinforced composites(32). Asi et al. produced GFRP-filled Al_2O_3 particles and investigated flexural strength. They determined that the optimum wt.% Al_2O_3 amounts was 10%(22). These studies found that above the optimum amounts, flexural strength was deteriorating.

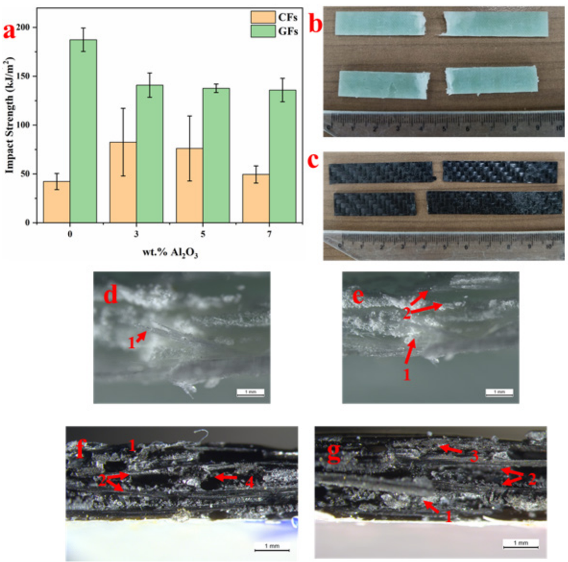

Figure 3. Impact performance of epoxy matrix composites (a) impact strength of GFRP/CFRP composites with varying wt.% Al_2O_3 (b,c) image of specimens after testing and stereomicroscope image of specimens after impact test (d) G0, (e) G5, (f) C0 and (g) C7

The results from the varying amounts of Al_2O_3 reinforcement on the composite from the Charpy impact test are illustrated in Fig. 3. The data shown are the average of three tests for each sample type. The impact strength is determined between 42.2 and 187.4 kJ/m^2. The highest impact strength was found in unreinforced GFRP, and there was a decrease in impact strength with Al_2O_3 reinforcement (Approximately 28% decrease with the reinforcement of 7 wt.% Al_2O_3). Compared to GFRP, CFRP showed much lower impact strength overall. On the other hand, there was a remarkable 80.22% increase in the impact strength of the CFRP with the addition of 3 wt.% Al_2O_3. Increasing the Al_2O_3 amount also had a negative effect on CFRP. The stereomicroscope images (Fig. 3 (d-g)) were shown the presence of fiber breaks (1), delamination (2), voids (3) and matrix breakage (4) in the fracture surfaces. Wang et al. prepared Al_2O_3-reinforced CFRP and investigated impact strength. They found that the optimum Al_2O_3 was 15 g/m^2 and with the increase of the reinforcement ratio to 20%, the impact strength decreased by approximately 16%(32).

Fig. 4 demonstrates the effect of Al_2O_3 for CFRP/GFRP composites on hardness behaviour. Hardness is obtained between 33.5 and 48.7 HBA. The maximum hardness value in both composite types was obtained in the samples reinforced with 3 wt.% Al_2O_3. Compared to the unreinforced samples, there was a 12.99% and 7% increase in hardness for CFRP and GFRP, respectively. Increasing the Al_2O_3 amount above 3 wt.% also had a negative effect on the hardness of both composite types. It's a general rule that the hardness of a material goes up as the filler increases. Fillers give epoxy resins their hardness, and as the amount of filler increases, so does the hardness of the epoxy(33). It was observed that agglomeration in CFRP composites decreased the impact and flexural strength with above 3 wt.% Al_2O_3; hence, a decrease in hardness is also observed. Similar results are also available in previous studies(33-35).

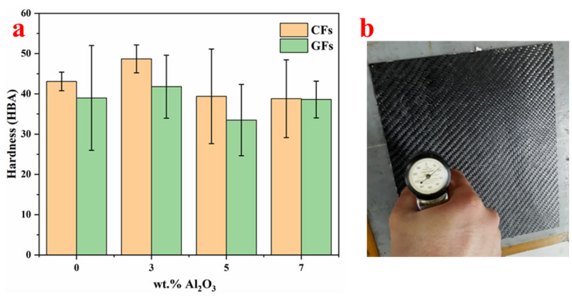

Figure 4. Hardness results of the composites (a) the hardness of composites with varying wt.% Al_2O_3 and (b) Barcoll hardness test view

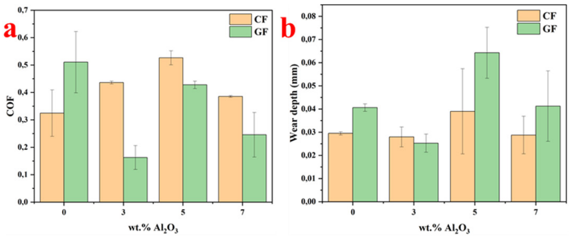

Figure 5. Wear test results of the composites (a) COF and (b) wear depth

The COF and wear depth of composites that originated from varying Al_2O_3 wt.% amounts are illustrated in Fig. 5. The average COF and wear depth values refer to at least three tests. The COF and wear depth values are between 0.1625-0.5264 and 0.0252-0.0642 mm, respectively. The composites' lowest COF and wear depth values were determined for the G3 samples. Studies in the literature show that the materials with the lowest COF and wear depth have the highest wear resistance (36-38). The highest COF was obtained for the C5 samples, and the maximum wear depth was observed G5 samples. In CFRP composites, adding Al_2O_3 increased the COF value compared to the unreinforced sample. In contrast, in GFRP composites, adding Al_2O_3 increased the COF value compared to the unreinforced sample. The lowest wear depth for both composite types was obtained in the samples reinforced with 3 wt.% Al_2O_3. Zhang et al. found the lowest COF and wear rate results for 4 wt.% nano-Al_2O_3 reinforced CFRP composites(27).

CONCLUSIONS

The GFRP and CFRP reinforced with Al_2O_3 composites are produced via the hand lay-up method and investigated the mechanical and tribological properties. The conclusions are as follows:

- The relative density of the composites generally decreased with Al_2O_3 reinforcement. Also, the relative densities of CFRP composites are higher compared to GFRP.
- The highest flexural strength values are obtained for 3 wt.% Al_2O_3 reinforced CFRP composites. Al_2O_3 reinforcement decreased the flexural strength of GFRP composites and this decrease increased with increasing Al_2O_3 amount.
- The highest impact strength was found in unreinforced GFRP, and there was a decrease in impact strength with Al_2O_3 reinforcement. On the other hand, there was an outstanding increase in the impact strength of the CFRP with the addition of 3 wt.% Al_2O_3.
- The maximum hardness value in both composite types were obtained in the samples reinforced with 3 wt.% Al_2O_3.
- The lowest COF and wear depth was found 3 wt.% Al_2O_3 reinforced GFRP composites.

As a result of the studies, it has been determined that the optimum Al_2O_3 ratio is 3 wt.%. Future research will focus on ensuring a more homogenous distribution of reinforcements in the epoxy as well as improved surface adherence between the reinforcement and the matrix.

CONFLICT OF INTEREST

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

AUTHOR CONTRIBUTION

Cantekin Kaykilarli: Investigation, Characterization, Writing-Review&Editing
Aymurat Haydarov: Production, Characterization, Writing.
Duygu Kose: Production, Characterization, Writing.
Hasibe Aygul Yeprem: Investigation, Supervision, Writing-Review&Editing

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